Equatorial Plasma Depletions Observed over Brazil - Impact on Safety Critical GNSS Navigation

Thomas Dautermann

Christoph Mayer

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Overview

- Measurements & station setup
- Observations in airglow and GPS
- Approach simulation with measured bubble parameters
- CCD Monitor Test
- Plasma bubble threat model proposal

Ionospheric Observations

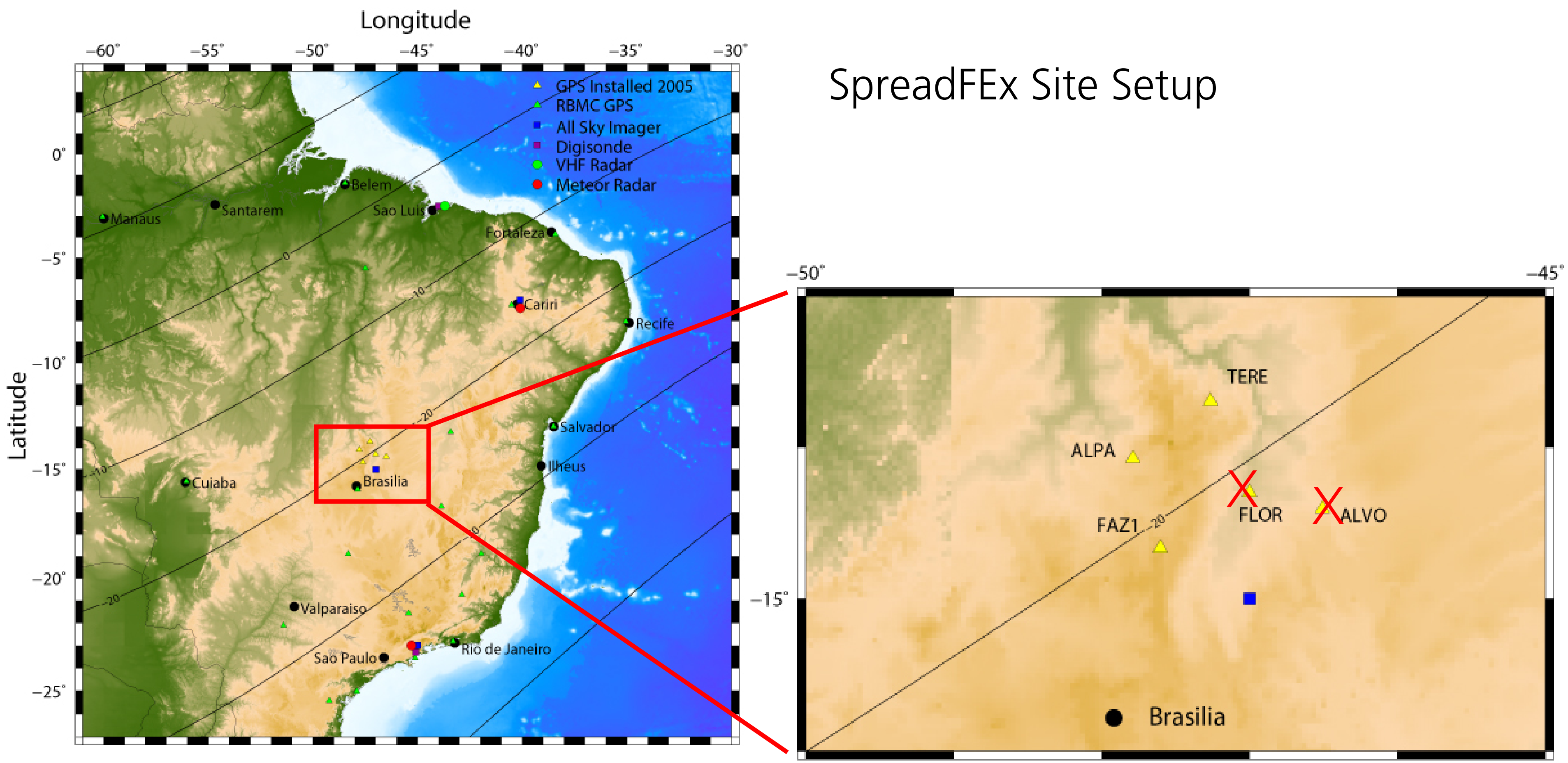
- Plasma bubbles mainly generated at magnetic equator due to Rayleigh-Taylor instability

- Airglow:
  - Charged ions emit faint radiation at 630 nm
  - Lower ionosphere ~250 to 280 km
  - Visible with an all-sky imager under clear sky

- GPS Ionospheric Delay:
  - Dependent on integrated signal path through ionospheric plasma
  - Main contribution from free electrons
  - Ionospheric F-Layer at 300-350km

Plasma Bubble Observations – Measurement Sites

SpreadFEx Site Setup



from Haase, Dautermann et al. (2009), Propagation of Plasma Bubbles Observed in Brazil from GPS and Airglow Data, Advances in Space Research, in press

IPP Superimposed on Airglow Images 2-Oct-2005

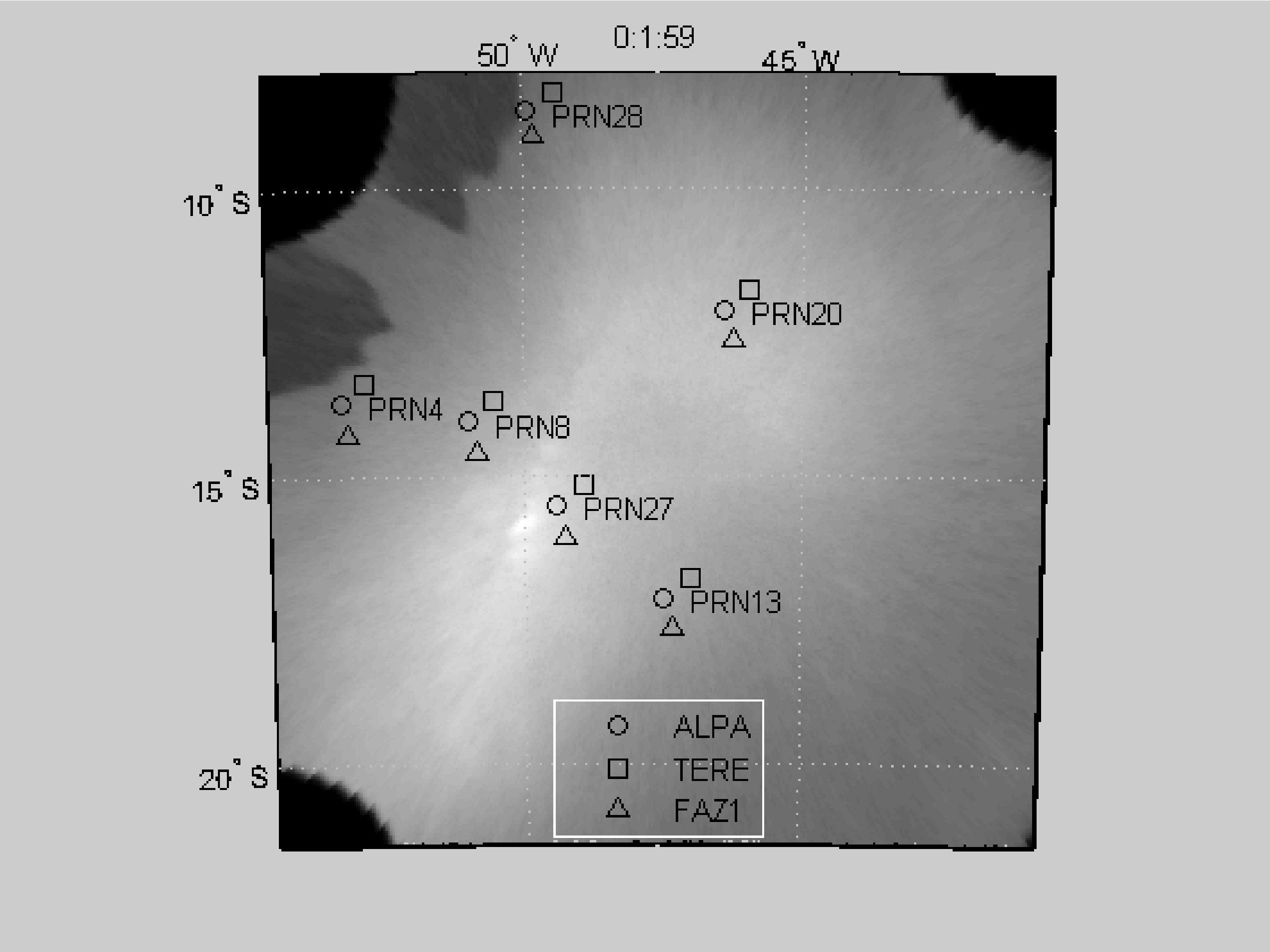
- Bright part → airglow
- Bubble forms as dark trough

IPP Order of Bubble Crossing:

1 - PRN4

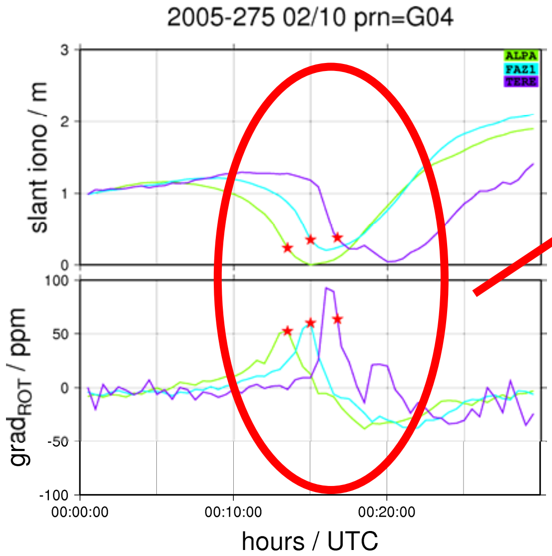
2 – PRN8

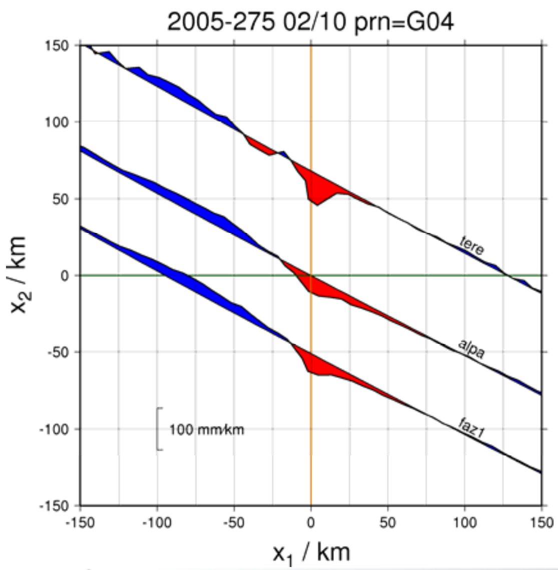
3 – PRN28



from Haase, Dautermann et al. (2009), Propagation of Plasma Bubbles Observed in Brazil from GPS and Airglow Data, Advances in Space Research, in press

Developing Bubble – PRN4 at 0:15 UTC



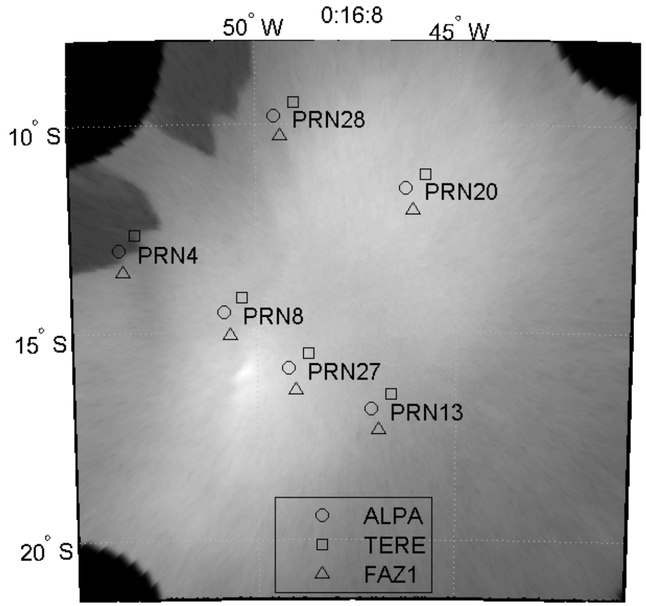


Gradient Detection

v_{front} = (174.9, -20.8) m/s
$|v_{front}|$ = 176.2 m/s
elev = 22 deg

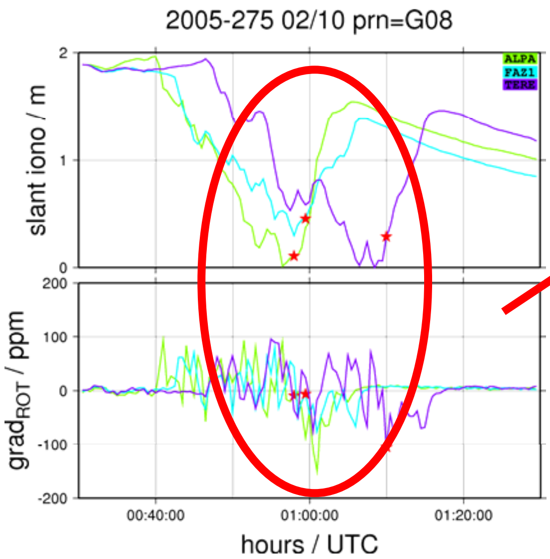
g(alpa) = -28.5 mm/km
g(faz1) = -32.1 mm/km
g(tere) = -51.3 mm/km

w(alpa) = 18.8 km
w(faz1) = 41.4 km
w(tere) = 88.3 km



*from Haase, Dautermann et al. (2009), Propagation of Plasma Bubbles Observed in Brazil from GPS and Airglow Data, Advances in Space Research, in press

Developing Bubble – PRN8 at ~1:00 UTC

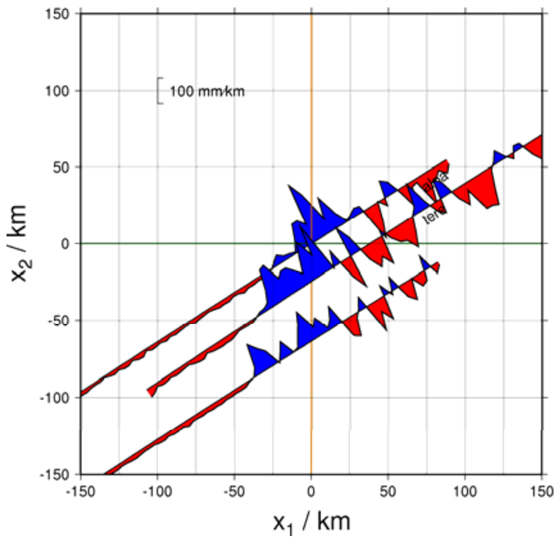


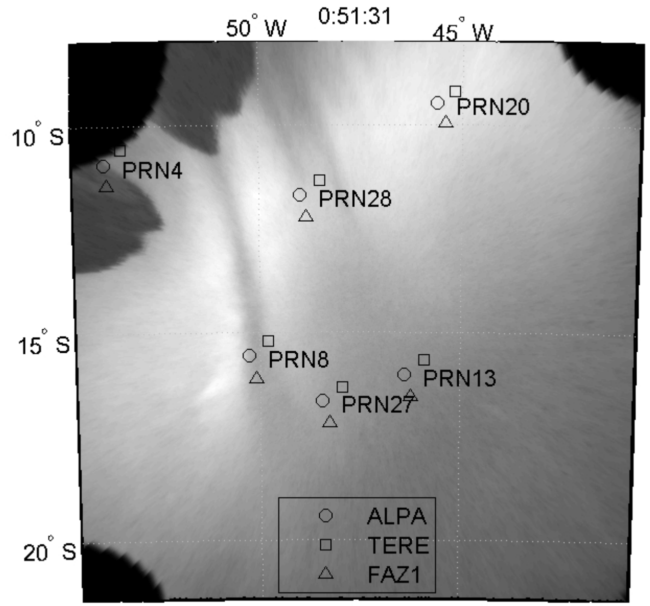
Gradient Detection

v_{front} = (116.6, 46.1) m/s
$|v_{front}|$ = 125.4 m/s
elev = 41 deg

g(alpa) = -84.6 mm/km
g(faz1) = -40.3 mm/km
g(tere) = -50.7 mm/km

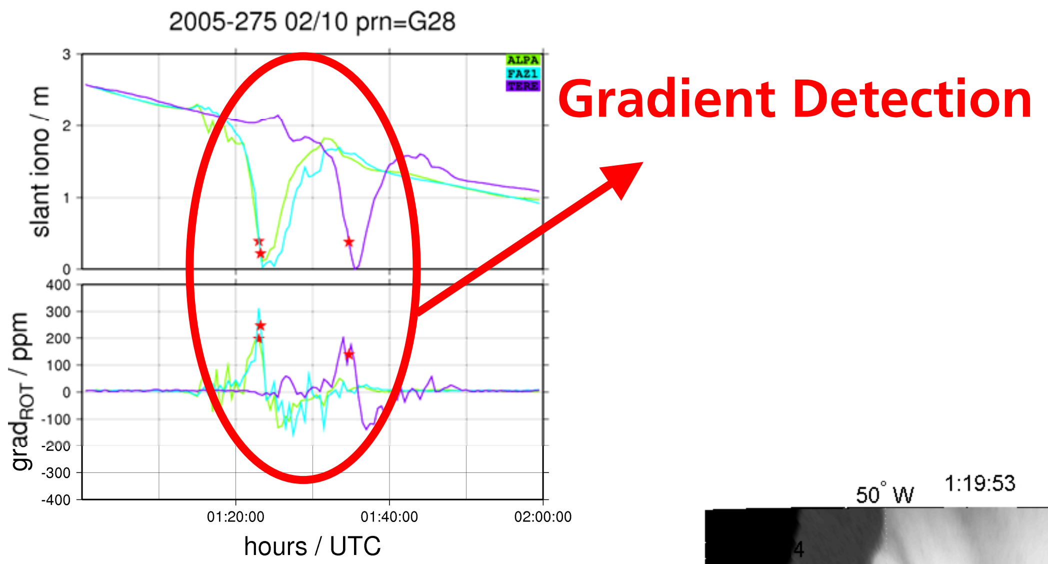
w(alpa) = 4.9 km
w(faz1) = 9.8 km
w(tere) = 4.7 km





*from Haase, Dautermann et al. (2009), Propagation of Plasma Bubbles Observed in Brazil from GPS and Airglow Data, Advances in Space Research, in press

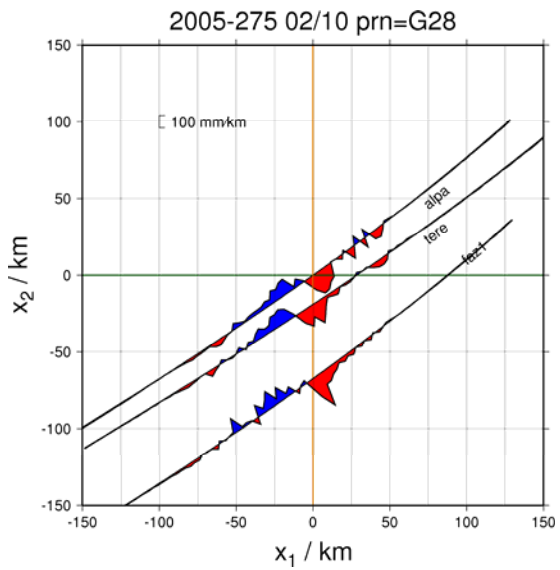
Developing Bubble – PRN28 at 1:20 UTC

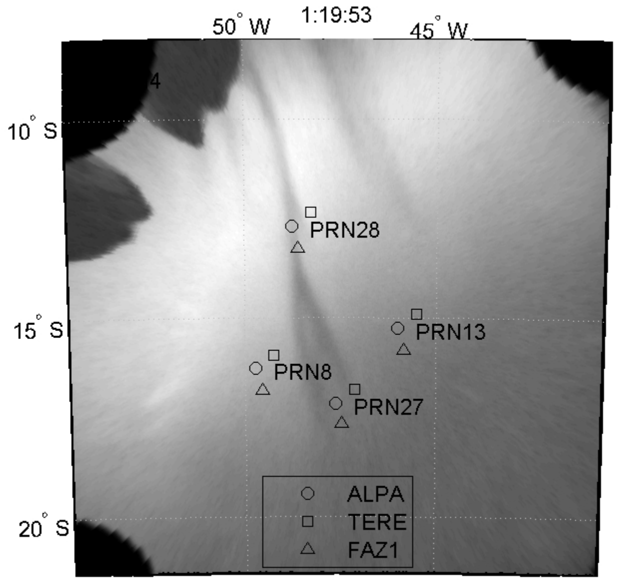


v_{front} = (88.3, 23.7) m/s
$|v_{front}|$ = 91.4 m/s
elev = 60 deg

g(alpa) = -139.0 mm/km
g(faz1) = -179.6 mm/km
g(tere) = -113.5 mm/km

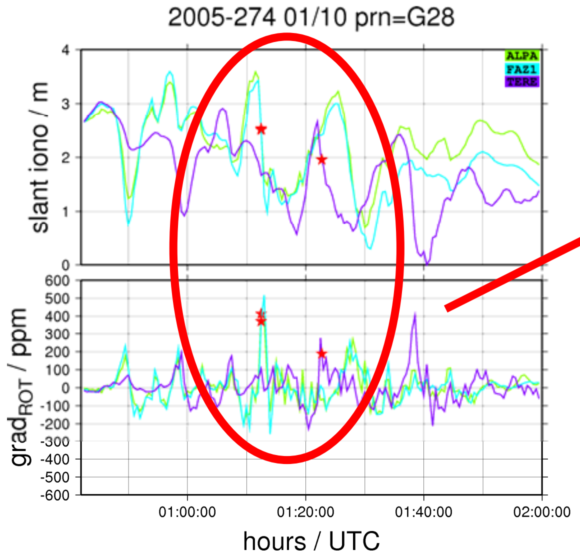
w(alpa) = 7.3 km
w(faz1) = 5.8 km
w(tere) = 17.5 km





*from Haase, Dautermann et al. (2009), Propagation of Plasma Bubbles Observed in Brazil from GPS and Airglow Data, Advances in Space Research, in press

Equatorial Plasma Irregularities – PRN28 on 1-Oct-2005

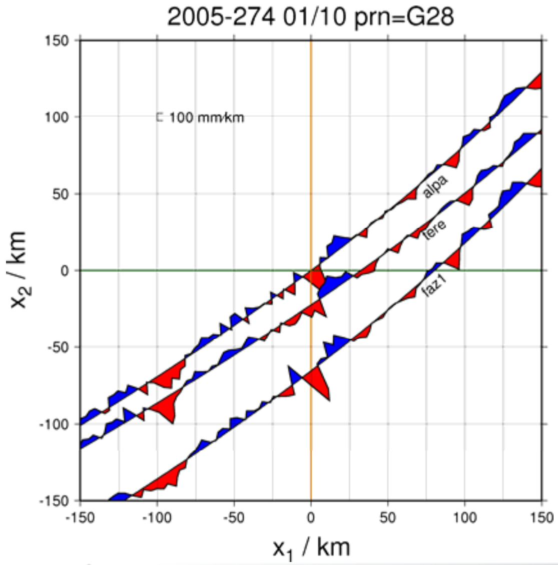


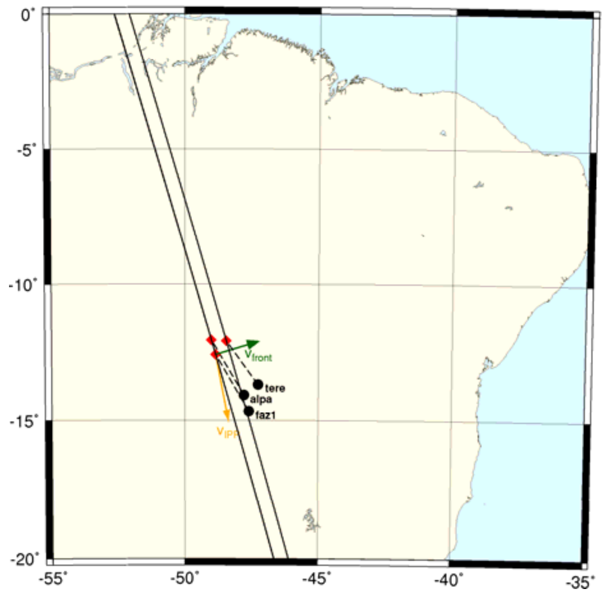
Irregularities can cause high gradients

v_{front} = (94.4, 27.5) m/s
$|v_{front}|$ = 98.4 m/s
elev = 53 deg

g(alpa) = -300.3 mm/km
g(faz1) = -338.2 mm/km
g(tere) = -134.1 mm/km

w(alpa) = 9.5 km
w(faz1) = 9.5 km
w(tere) = 4.8 km





Parameter Summary

decreasing velocity

increasing gradient

YYYY-DOY	dd/mm	HH:MM:SS	prn	#s	elev	lat	lon	v	azm(v)	g	gMin	gMax	w(km)	stns	bubble drop
2005-275	02/10	00:15:05	G04	3	22	-12.4	-53.8	176	97	32	28	51	41	**alpa**,faz1,tere	-1.4
2005-275	02/10	00:15:05	G04	3	22	-12.4	-53.8	176	97	32	28	51	47	alpa,**faz1**,tere	-1.4
2005-275	02/10	00:14:20	G04	3	22	-12.5	-53.8	177	97	32	28	51	32	alpa,faz1,**tere**	-1.2
2005-275	02/10	01:04:45	G08	3	41	-16.0	-49.8	125	68	51	40	85	5	alpa,**faz1**,tere	-0.4
2005-275	02/10	01:03:55	G08	3	41	-16.0	-49.8	130	79	54	43	91	34	alpa,faz1,**tere**	-1.1
2005-275	02/10	01:27:00	G28	3	60	-12.6	-48.4	85	75	148	121	192	7	**alpa**,faz1,tere	-1.8
2005-275	02/10	01:26:30	G28	3	60	-12.6	-48.4	91	75	139	114	180	7	alpa,**faz1**,tere	-1.9
2005-275	02/10	01:26:30	G28	3	60	-12.6	-48.4	87	78	152	124	197	7	alpa,faz1,**tere**	-1.7
2005-274	01/10	01:15:55	G28	3	53	-12.1	-48.4	98	74	300	134	338	9	**alpa**,faz1,tere	-1.5
2005-274	01/10	01:16:20	G28	3	53	-12.1	-48.4	101	74	293	131	329	5	alpa,**faz1**,tere	-1.8
2005-274	01/10	01:31:35	G28	3	60	-12.6	-48.4	96	75	158	140	229	5	alpa,faz1,**tere**	-1.7

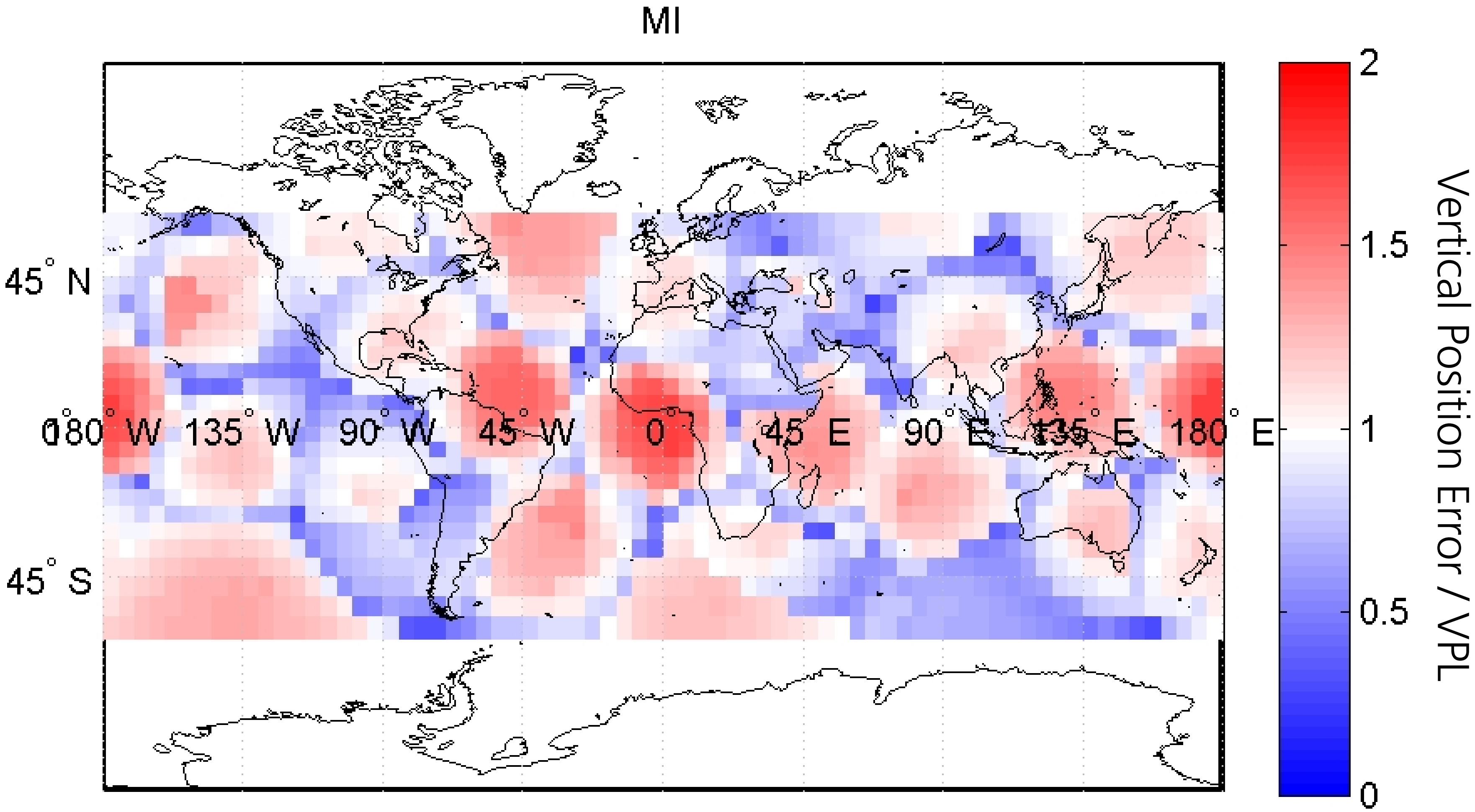
Equatorial Plasma Irregularities

Increasing Depth

Impact of the Measured Bubble on GBAS Integrity

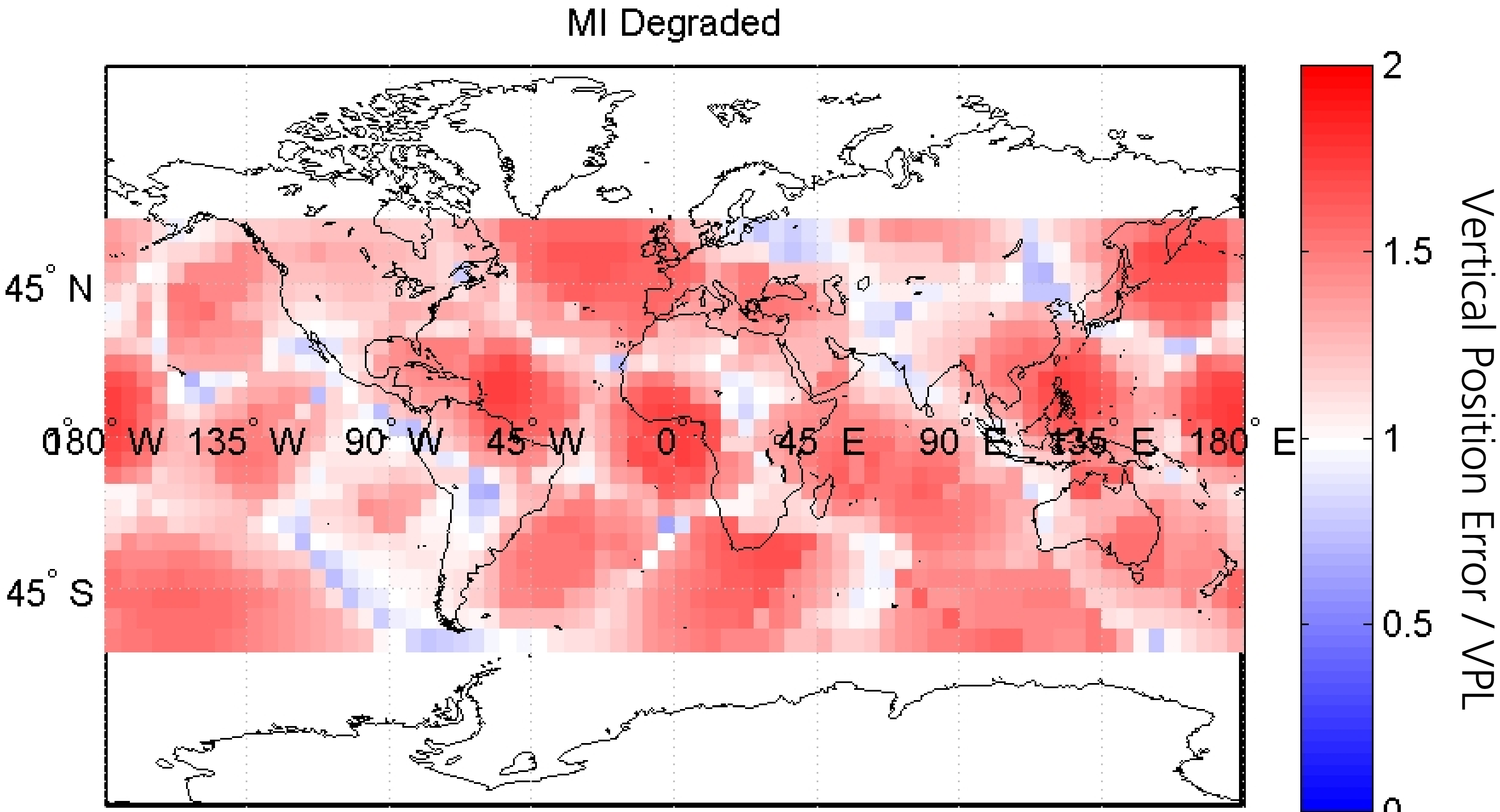
- Bubble with ΔDelay=-2m, as measured
- Worldwide GBAS Approach Simulation on 5°x5° Grid
- Approach direction 90° starting at 10,000ft
- Protection Level Calculation follwing RTCA 253C:
  - σ_{iono}=4 mm/km
  - σ_{pr_gnd} → GAD C
  - σ_{air} → AAD B
  - σ_{tropo} → standard atmosphere
- GPS Constellation of 2 October 2005
- Using Worst Case Setup from Harris et al. (2009), i.e. Front/Bubble moved with airplane (IPP)
- Assessment in Terms of MI: Error/VPL and HMI: Error/VAL

Misleading Information Simulation



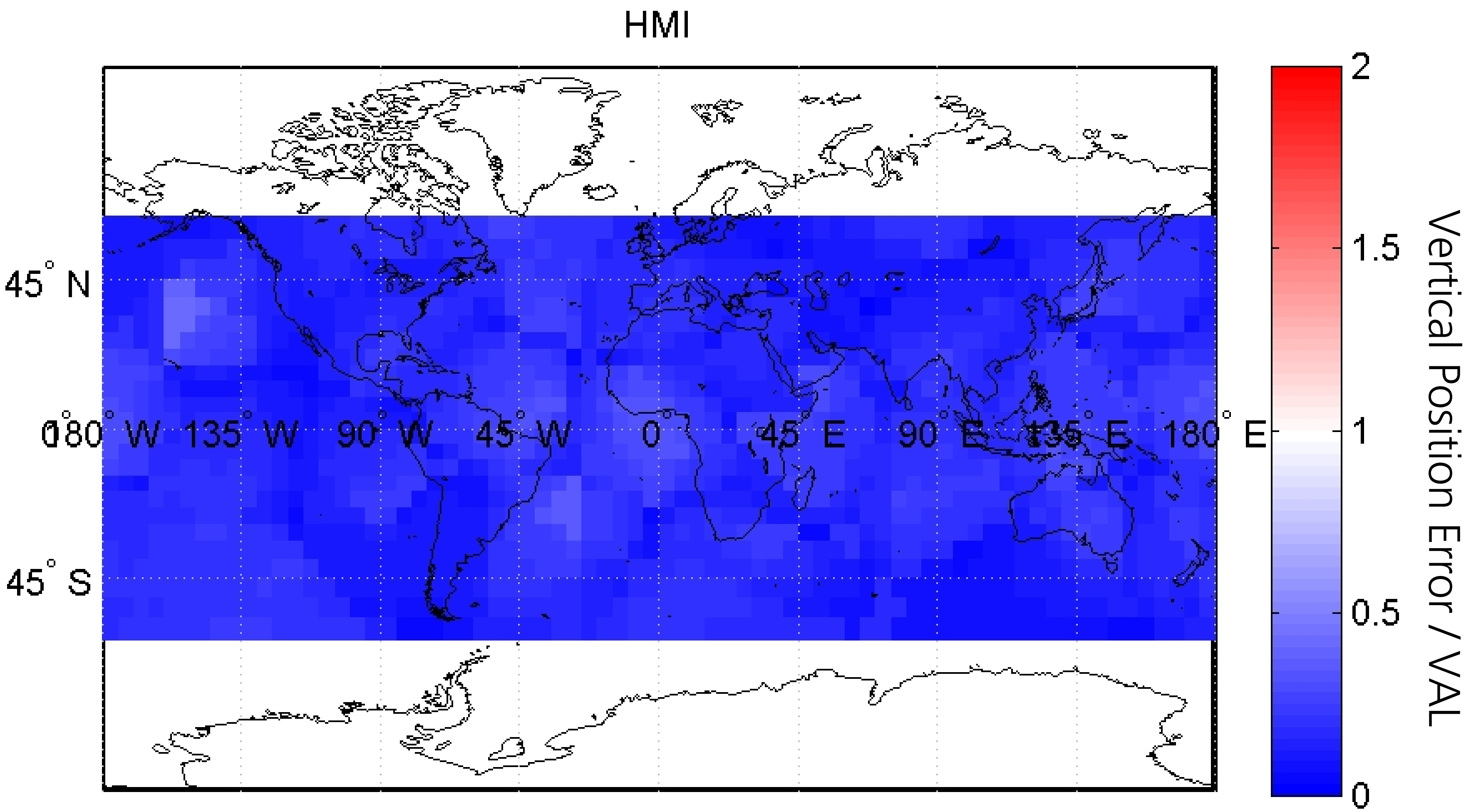
- Full Constellation of 2 October 2005

Misleading Information Simulation



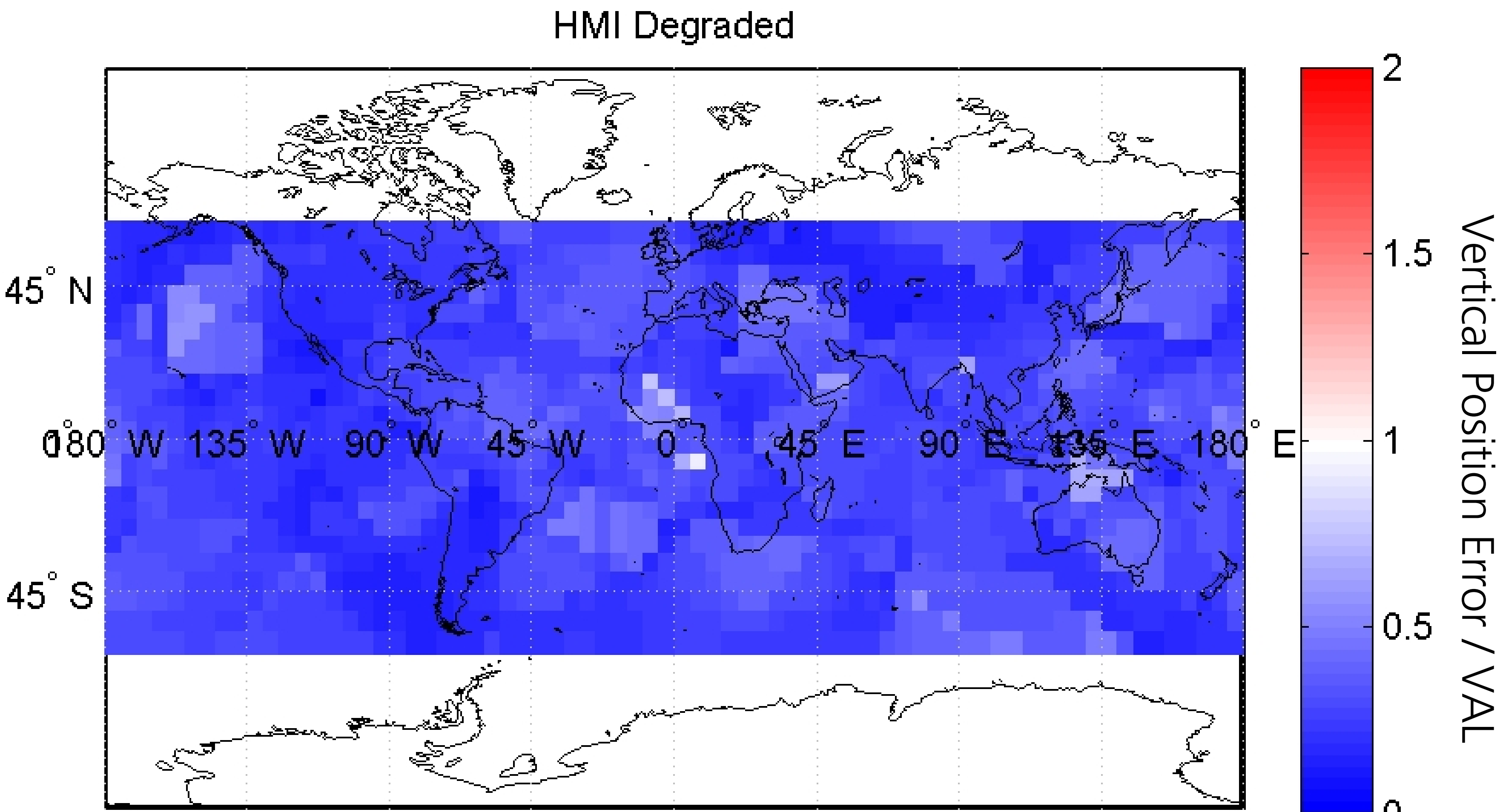
- One Satellite in view removed Constellation of 2 October 2005

Misleading Information Simulation



- Full Constellation of 2 October 2005

Misleading Information Simulation



- One Satellite in view removed Constellation of 2 October 2005

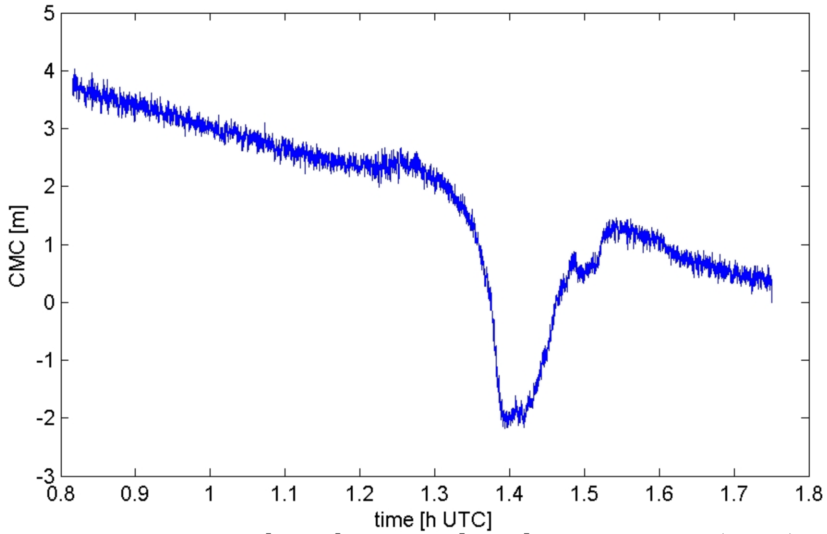
Bubble Simulation in the MASTER GNSS Simulator & CCD Monitor Test

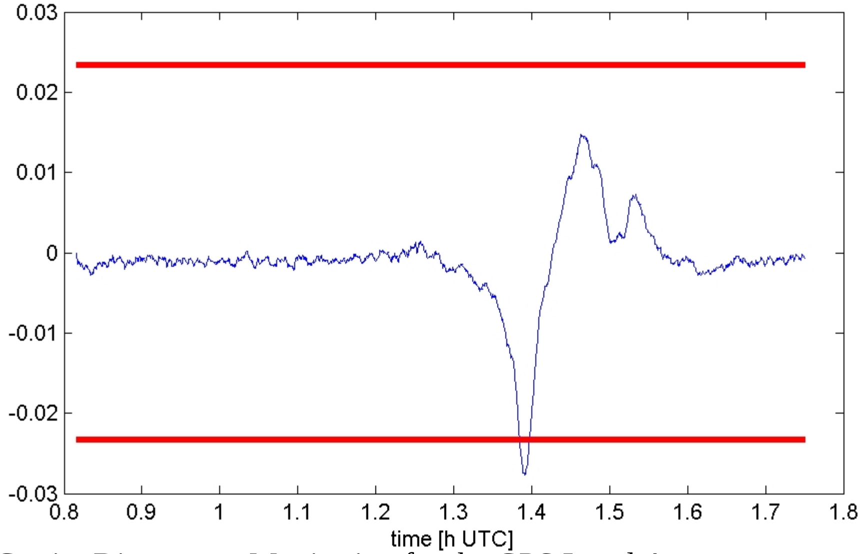
- Observed Plasma Bubble is reproduced at 2Hz for PRN28 and site Faz1 in Spirent GNSS Simulator and result is tested in GBAS CCD Monitor (Simili & Pervan, 2006)

Monitor Parameter	Definition	Value
T	Sample Time	0.5sec
$k_{ffd,mon}$	Constant	5.83
τ_d	Time Constant	30sec
σ_d	std. dev. of d_2 (fault free test metric)	0.00399 m/s

*

$$\text{Threshold} = k_{ffd,mon}\sigma_d = 0.0233\text{m/s}$$ *

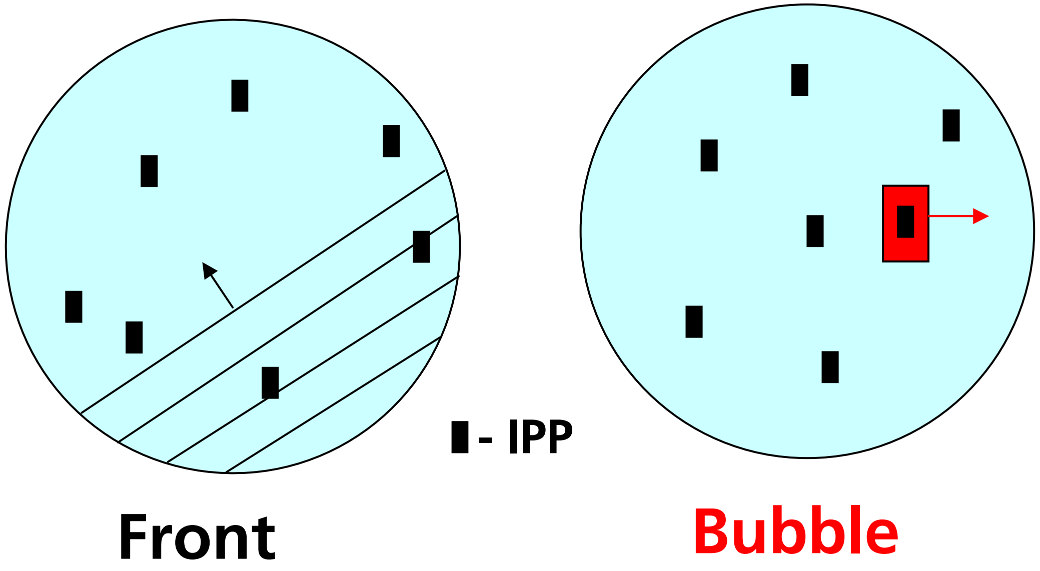




*Dwarakanath V. Simili and Boris Pervan (2006), Code-Carrier Divergence Monitoring for the GPS Local Area Augmentation System, Proceedings of the Position, Location and Navigation Symposium

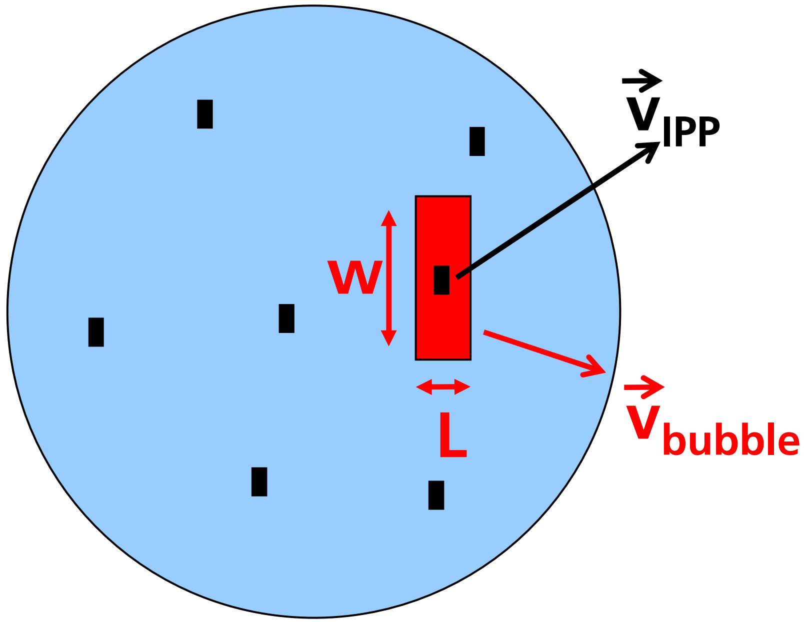
2D Threat Model Proposal for Plasma Bubbles

- Normal front model may not cover all eventualities, since it would always affect satellites in a row, a bubble might only affect one satellite
- Vector sum of IPP velocity (direction, speed) and Bubble velocity (direction, speed) can combine in different way to generate worst case situations

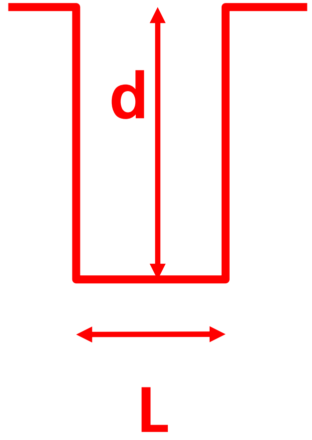


Proposed Threat Model

- IPP speed v_{IPP} and Bubble speed V_{bubble} in magnitude and direction
- Width w
- Length L
- Depth d



- Parameter space needs to be established through observations
- Screening needs to account for worst case consideration of parameter combination



Thank you for your attention !

Thanks to:

F. São Sabbas (INPE, Brazil)

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D. Pautet, M. Taylor (USU, Utah)

D. Fritts (CORA, Colorado)